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Enabling Fault Tolerance with Gate Set Tomography

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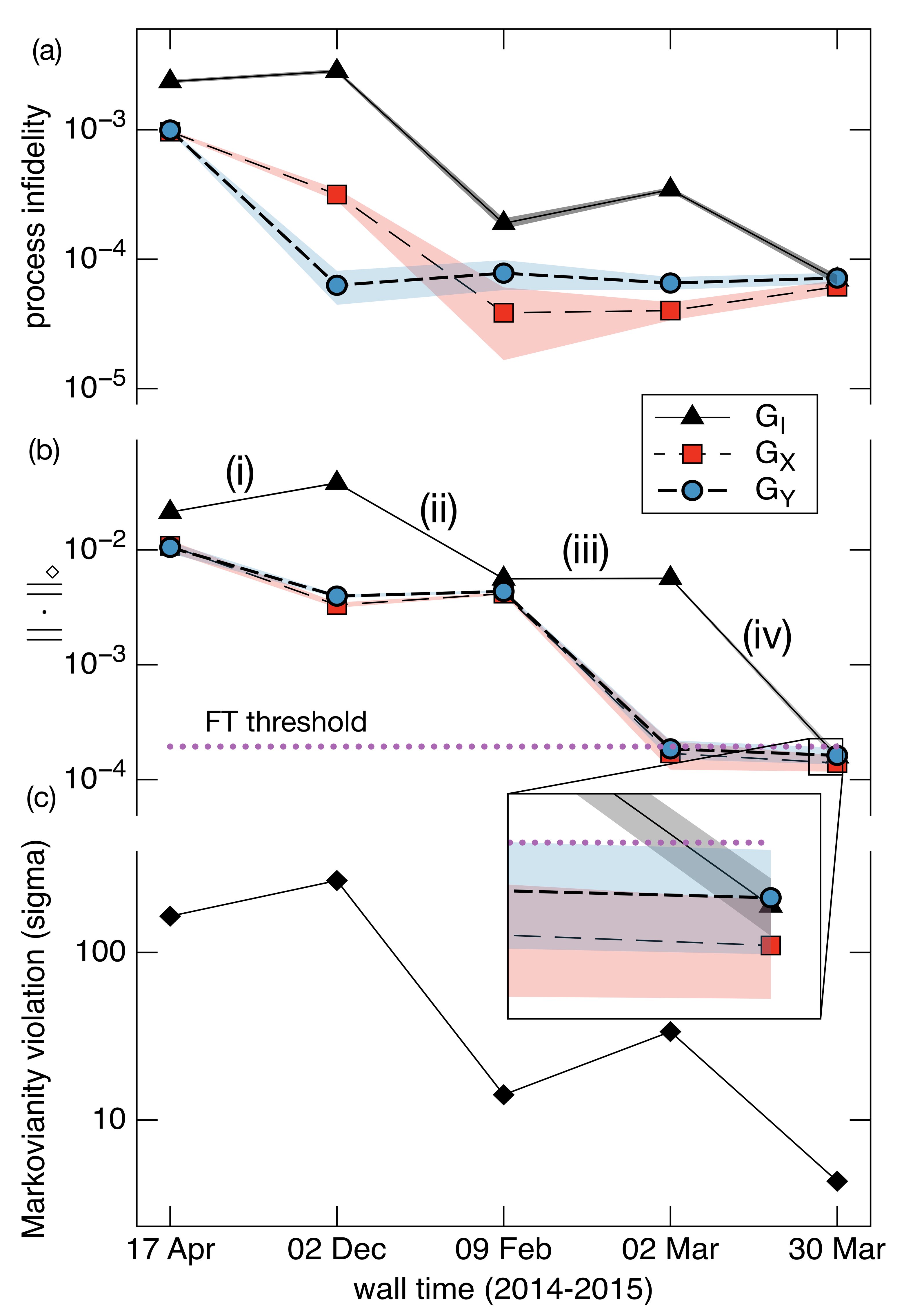
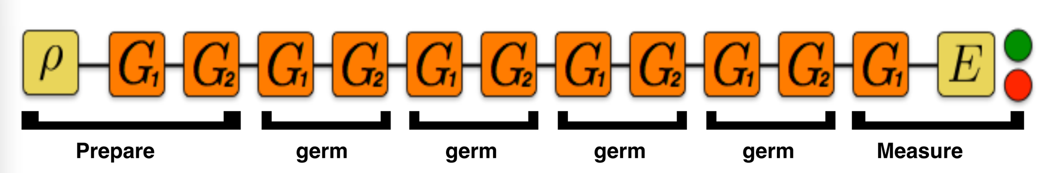
We used **gate set tomography (GST)** to debug 1- and 2-qubit gates and certify their suitability for fault tolerance. In each of five runs, GST provided detailed, precise, and reliable information about: (1) **error rates** (including diamond norms); (2) **error types** (coherent, dephasing, etc); and (3) **non-Markovian errors**. This let us achieve **10^{-4} *diamond norm* error** in single qubit gates. Our "pyGSTi" software is now **open source** at `http://pygsti.info`.

Capabilities vs Protocols	No Calibration Required	Detailed Debug Info	Efficiently Certifies ◇-norm	Detects Non-Markovian noise
Randomized Benchmarking	✔	✘	✘	✔
Process Tomography	✘	✔	✘	✘
Gate Set Tomography	✔	✔	✔	✔

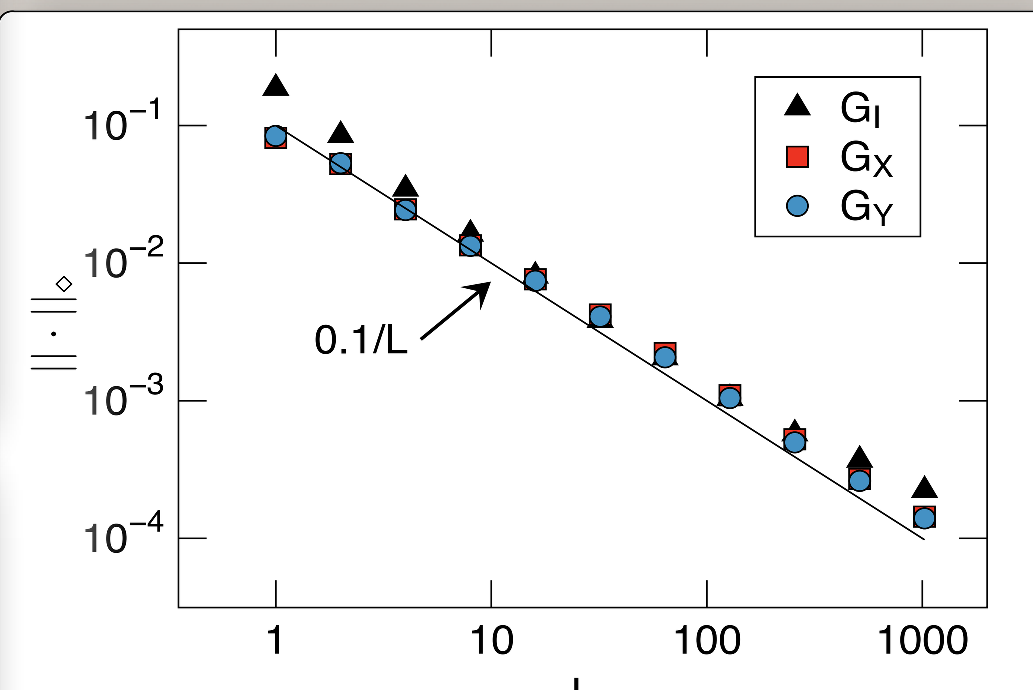
Our goals in developing GST

✔1: Certify achieving FT threshold -- in diamond norm!
✔2: Debugging -- full, calibration-free characterization.
✔3: Accuracy -- Heisenberg scaling w/sequence length.
✔4: Detect non-Markovianity (& diagnose if possible).

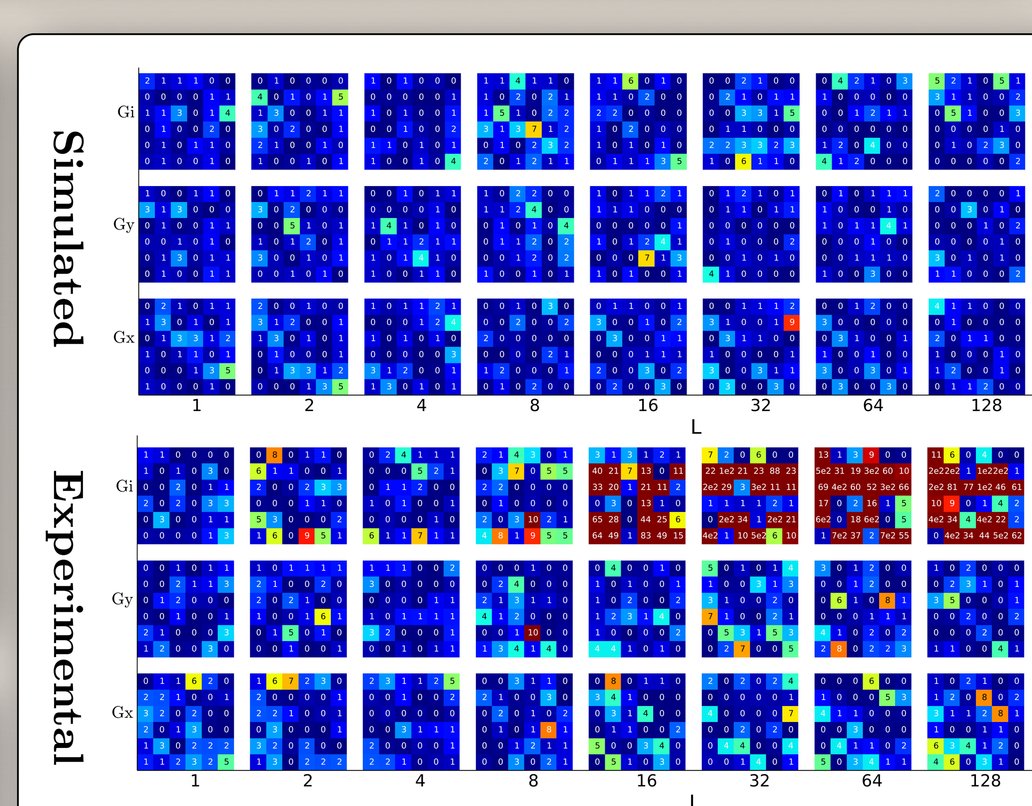




A typical GST experiment. A "germ" -- one of several short sequences designed to single out particular parameters -- is repeated many times to amplify errors, and bookended by short "fiducial" sequences.



GST estimation error (diamond norm) scaling. *Simulated* GST (with assorted *known* true gates), shows Heisenberg scaling: The diamond norm error scales as 1/L with max. sequence length



Detecting non-Markovianity with GST. Each box represents a (chi-squared) measure of non-Markovianity for a particular gate sequence. Red boxes indicate un-fittable data points that suggest strongly non-Markovian effects. Simulated data (top) illustrates perfectly Markovian behavior. Experimental data (bottom) has significant non-Markovianity. The non-Markovian signature is strongest for gate sequences involving repetitions of the idle gate, suggesting that the idle gate needs to be fixed. With this information, we upgraded the dynamical decoupling on this gate for subsequent experiments and eliminated non-Markovian behavior.

Achieving threshold by debugging

At left, experimental performance of our trapped ion qubit over time, culminating on 30 March 2015. GST results guided incremental improvements:

(i) Stabilized temperature of microwave amplifier, applied active feedback for drift control.

(ii) Improved trap stability, changed trap (Thunderbird -> HOA-2).

(iii) Changed idle (G_I) gate from "do nothing for one cycle" to dynamically decoupled pulse sequence.

(iv) Changed identity gate from first-order dynamical decoupling to second-order dynamical decoupling.

(FINAL) Demonstrated diamond norm error below 1.94×10^{-4} with 95% confidence.

GST beyond one qubit

We used GST on a 2-qubit system (no individual addressing -- only symmetric subspace is visible) to fully characterize 2-qubit gates.

M-S gate with 99.6% fidelity

Gate	$1-F$	$\|\cdot\|_\diamond$
Identity	$1.6 \cdot 10^{-3}$	$5.7 \cdot 10^{-2}$
$X \otimes X$	$3.7 \cdot 10^{-4}$	$5.5 \cdot 10^{-2}$
$Y \otimes Y$	$7.0 \cdot 10^{-5}$	$5.3 \cdot 10^{-2}$
Mølmer-Sørensen	$4.2 \cdot 10^{-3}$	$7.8 \cdot 10^{-2}$

GST is now publicly available

Two options for use:

1. Open-source software (pyGSTi): www.pygsti.info/.

2. Web app: prod.sandia.gov/gst/. (Email **`pygsti@sandia.gov`** to get a login account.)

Outputs: Gate matrices, diamond distances, infidelities, non-Markovianity quantification, error bars, and more!

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